# HIGH PRESSURE MAGNETO-OPTICAL STUDIES OF ELECTRONS IN GaSb/AlSb/InAs HETEROSTRUCTURES

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# Introduction

## Background

☞ GaSb/AlSb/InAs heterostructures ⇒ potential for high-speed speed electronic devices and infrared detectors and sources.

☞ Type-II broken gap (InAs/GaSb) to Type-II staggered (InAs/AlSb) as a function of alloy composition (the crossover occurs at x = 0.3 at 1 atm).

☞ Similar tuning of the band alignment can be effected via hydrostatic pressure.

☞ Outstanding problem ⇒ *Excess Electrons.*

Possible Sources:Surface donors in the GaSb cap-layer, metastable DX-like bulk states in AlSb, and Tamm-like states at the interfaces with InAs. H. Kroemer, C. Nguyen and B. Brar, J. Vac. Sci. Technol. B **10**, 1769 (1992).

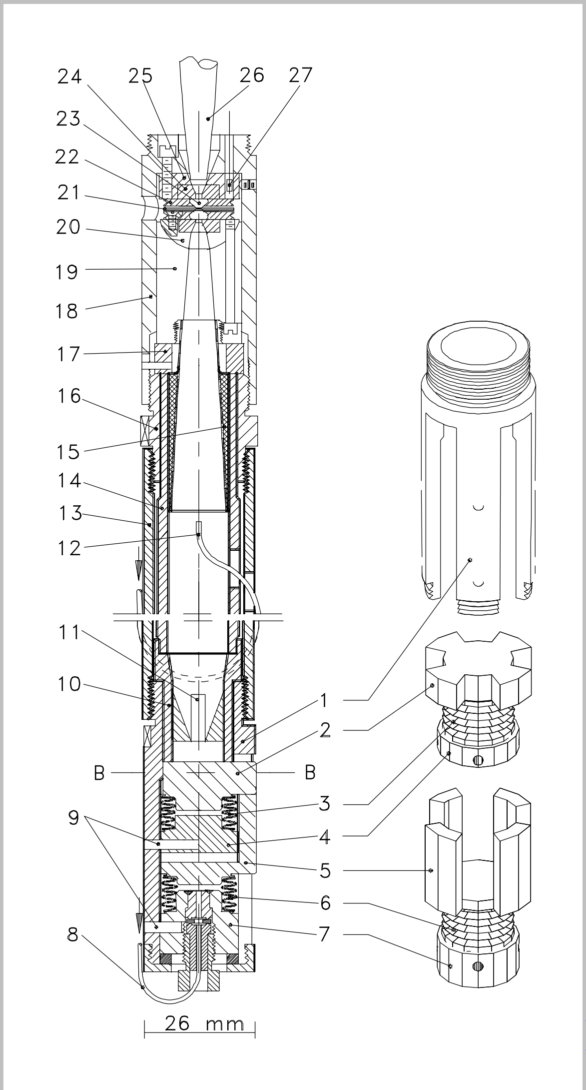
## Motivation

To probe the origin of the excess electrons by studying the effects of hydrostatic pressure on the cyclotron resonance(CR) in a single GaSb/AlSb/InAs heterostructure.

**Work supported in part by NSF grant DMR 9624029 and ONR contract N000149710858.**

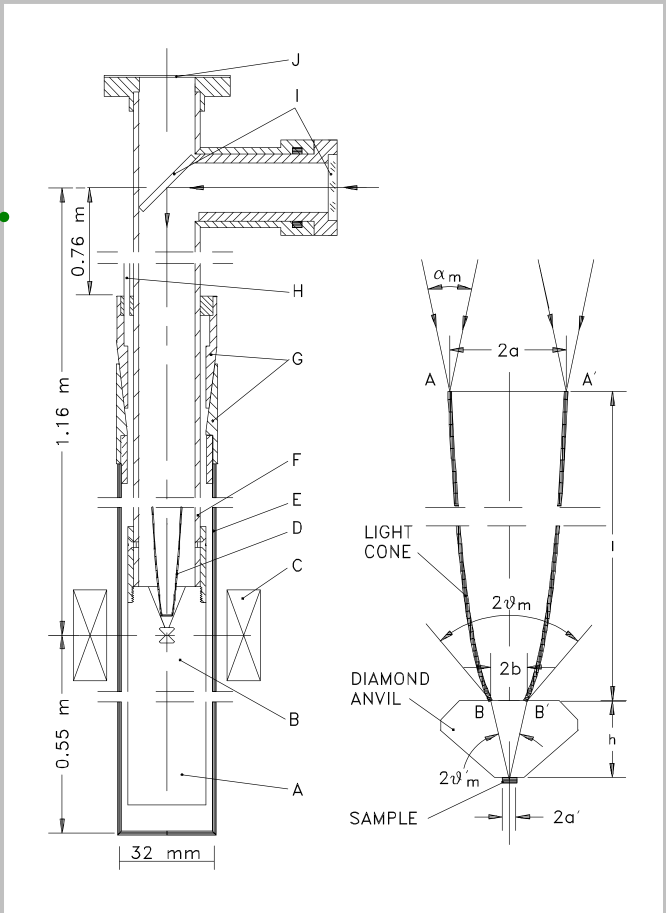
# Experimental Setup

**FIR magneto-spectroscopy DAC apparatus tunable *in situ* over 0-150 kbar, 2-300 K, 0-9 T.**




## Design Features:

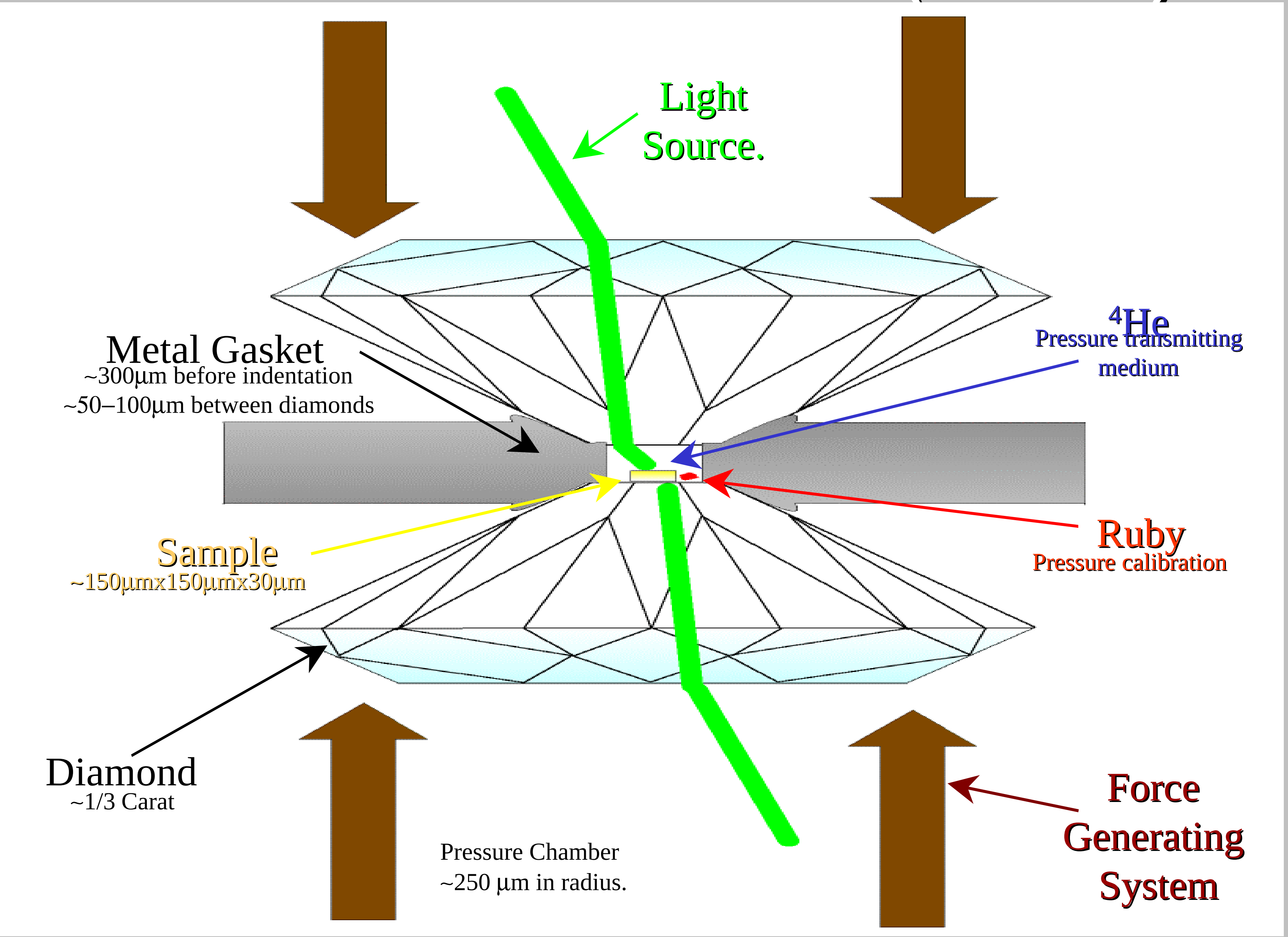
- Multi-bellows ram(doubles force).
- Focusing light cones.
- Ga:Ge detector (80-240 $cm^{-1}$).
- Visible + FIR access.




**Multi-bellows ram(US patent 5693345)**

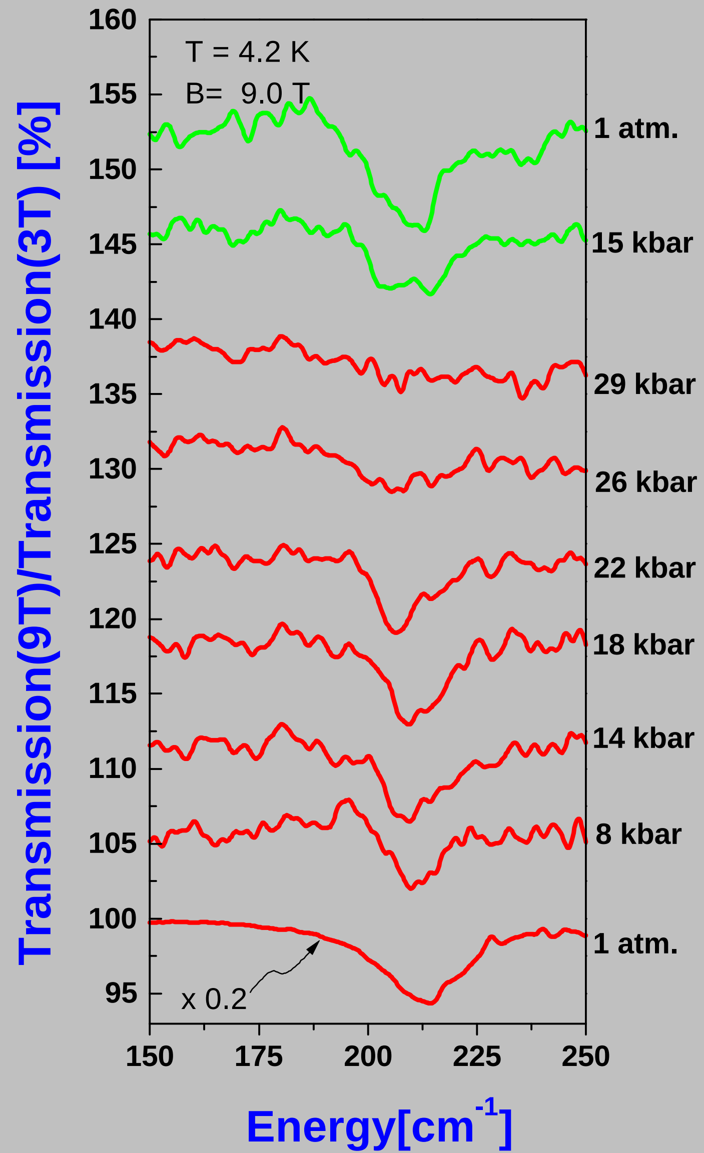
**Chen and Weinstein, Rev. Sci. Instrum., 67, 2883(1996).**

# Diamond Anvil Cell(DAC)




**Schematics of the opposed Bridgman Anvil configuration.**

# Cyclotron Resonance(CR) Quenching




Effects of pressure on the Fourier transform FIR magneto-transmission at 9T and 4.2 K. The spectra shown in green lines was obtained by releasing the pressure after observing the CR quenching.

# Model Solid Theory

☞ Model-Solid Theory relates the energy levels in bulk semiconductors to a common reference level.

**C.G. Van de Walle, Phys. Rev. B 39, 1871 (1989)**

☞ Strain, due to applied pressure or to internal mismatch, affects the position of the energy bands.

*i=valence band, conduction band*

*j = AlSb, InAs, GaSb*

$$\Delta E_i^j = a_i^j \times \frac{\Delta\Omega^j}{\Omega^j} = a_i^j \times \left[\frac{\Delta a_x^j}{a_x^j} + \frac{\Delta a_y^j}{a_y^j} + \frac{\Delta a_z^j}{a_z^j}\right]$$

Average band energy position.

Deformation potential.

Fractional volume change.

$$\Delta a_x^j = \Delta a_y^j = a_x^j - a_x^{AlSb}$$

$$\frac{\Delta a_z^j}{a_z^j} = -2\frac{C_{12}^j}{C_{11}^j} \times \frac{\Delta a_x^j}{a_z^j}$$

☞Splitting of the valence band with strain:

*Shear deformation potential for a strain of tetragonal symmetry.*

$$dE_{001}^j = 2b^j \times \left(\frac{\Delta a_z^j}{a_z^j} - \frac{\Delta a_x^j}{a_x^j}\right)$$

$$\Delta E_{hh}^j = \frac{\Delta_0^j}{3} - \frac{dE_{001}^j}{2}$$ J=3/2, $m_j = \pm 3/2$

$$\Delta E_{lh}^j = -\frac{\Delta_0^j}{6} + \frac{dE_{001}^j}{4} + \frac{1}{2}\sqrt{\left(\Delta_0^j\right)^2 + \Delta_0^j \times dE_{001}^j + \frac{9}{4}\left(dE_{001}^j\right)^2}$$ J=3/2, $m_j = \pm 1/2$

$$\Delta E_{SO}^j = -\frac{\Delta_0^j}{6} + \frac{dE_{001}^j}{4} - \frac{1}{2}\sqrt{\left(\Delta_0^j\right)^2 + \Delta_0^j \times dE_{001}^j + \frac{9}{4}\left(dE_{001}^j\right)^2}$$ J=1/2, $m_j = \pm 1/2$

☞Pressure effects(Murnaghan's equation of state):**T.M. Ritter, PhD. Thesis, SUNY at Buffalo (1/97), unpublished.**

First pressure derivative of the bulk modulus.

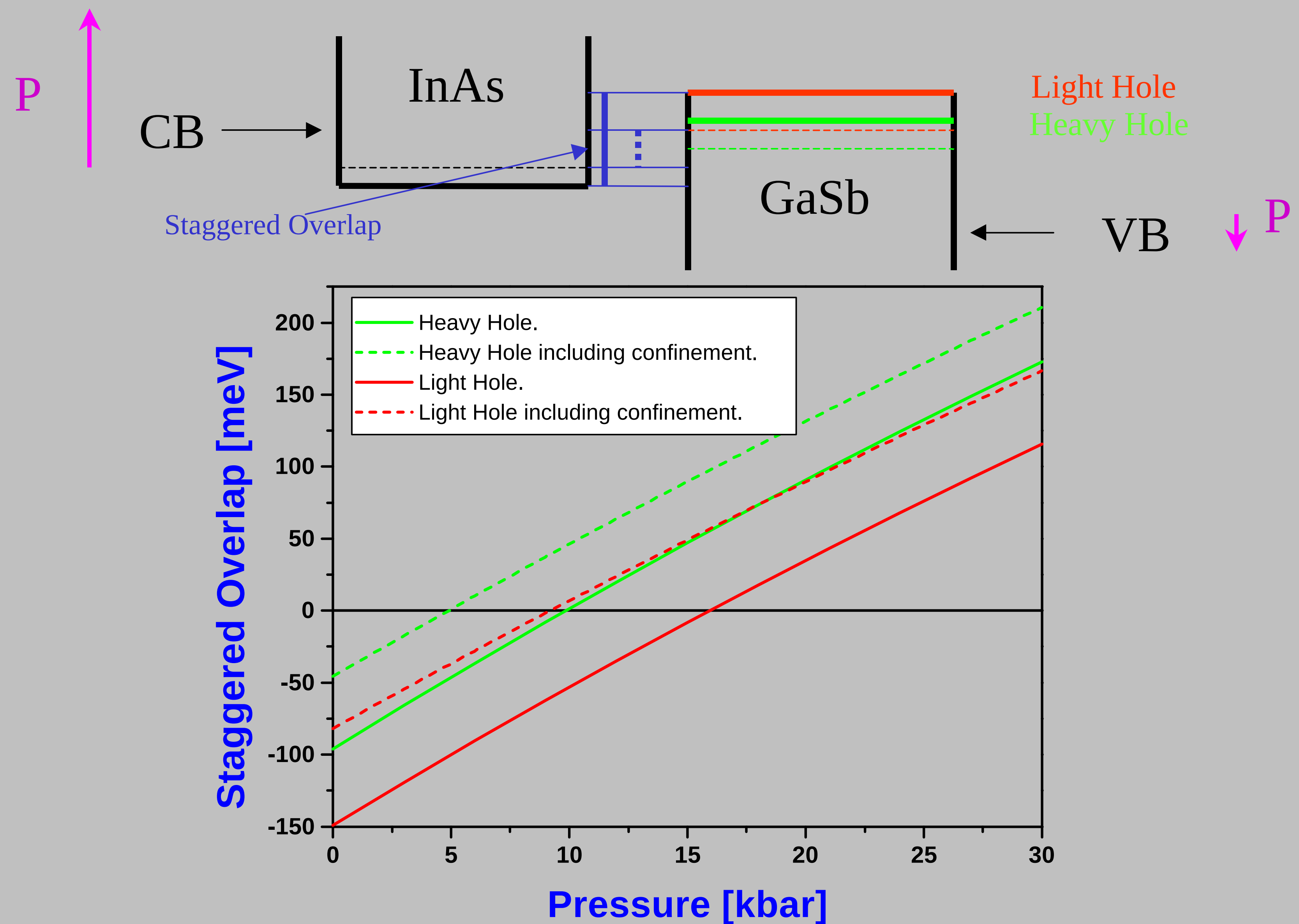
$$\Delta a_x^j(p) = \Delta a_y^j(p) = a_x^j(p) - a_0^{AlSb}$$

$$a_x^j(p) = a_y^j(p) = a_z^j(p) = a_0^j \times \left[1 + \frac{B_1^j}{B_0^j}p\right]^{-\frac{1}{3B_1^j}}$$

1atm lattice constant

Bulk modulus

# Calculated Results for Flat-Band

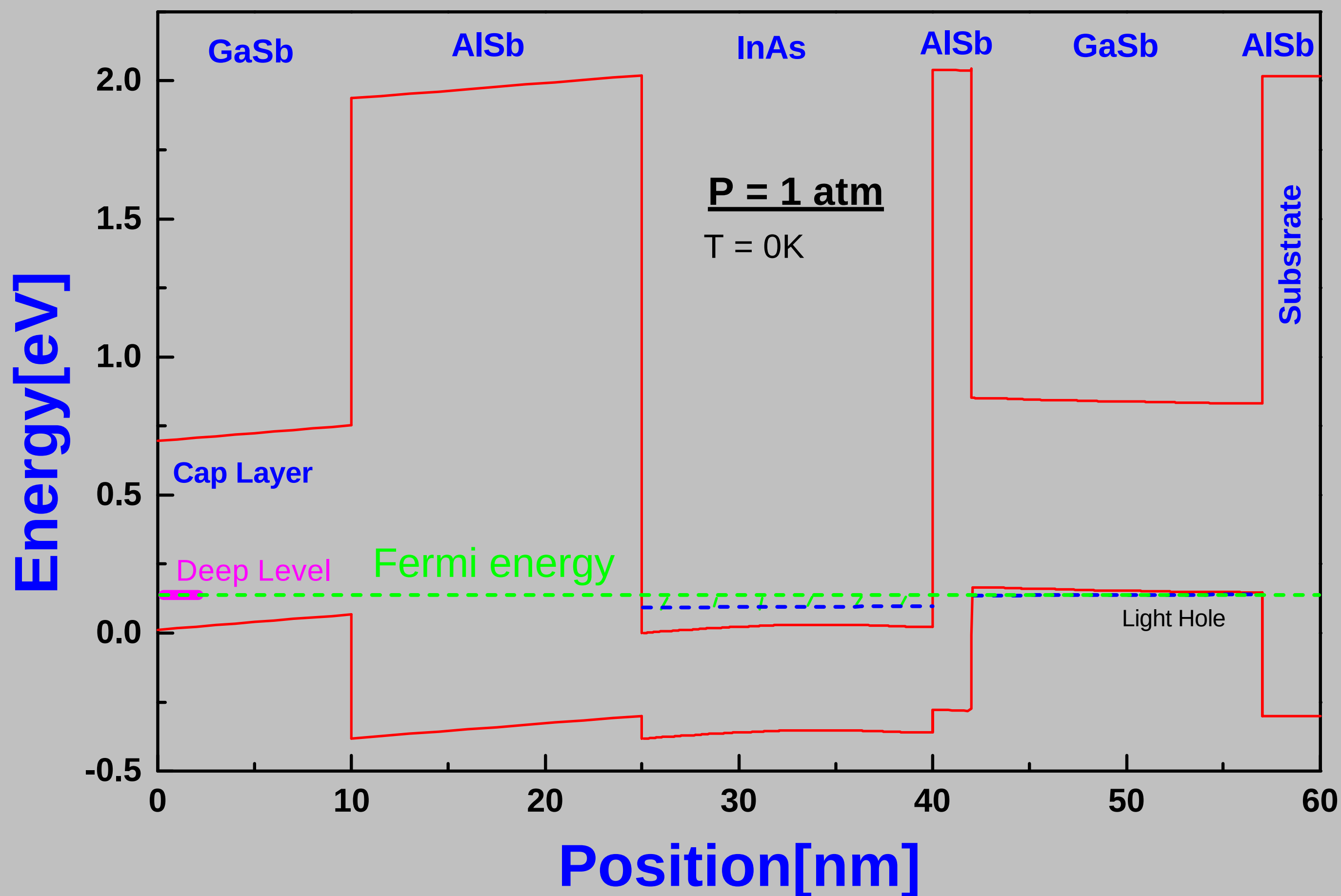



Staggered overlap as a function of pressure. The flat band calculation predicts the extinction of the intrinsic electron density at ~9 kbar.

# Calculated Results Including Self Consistency

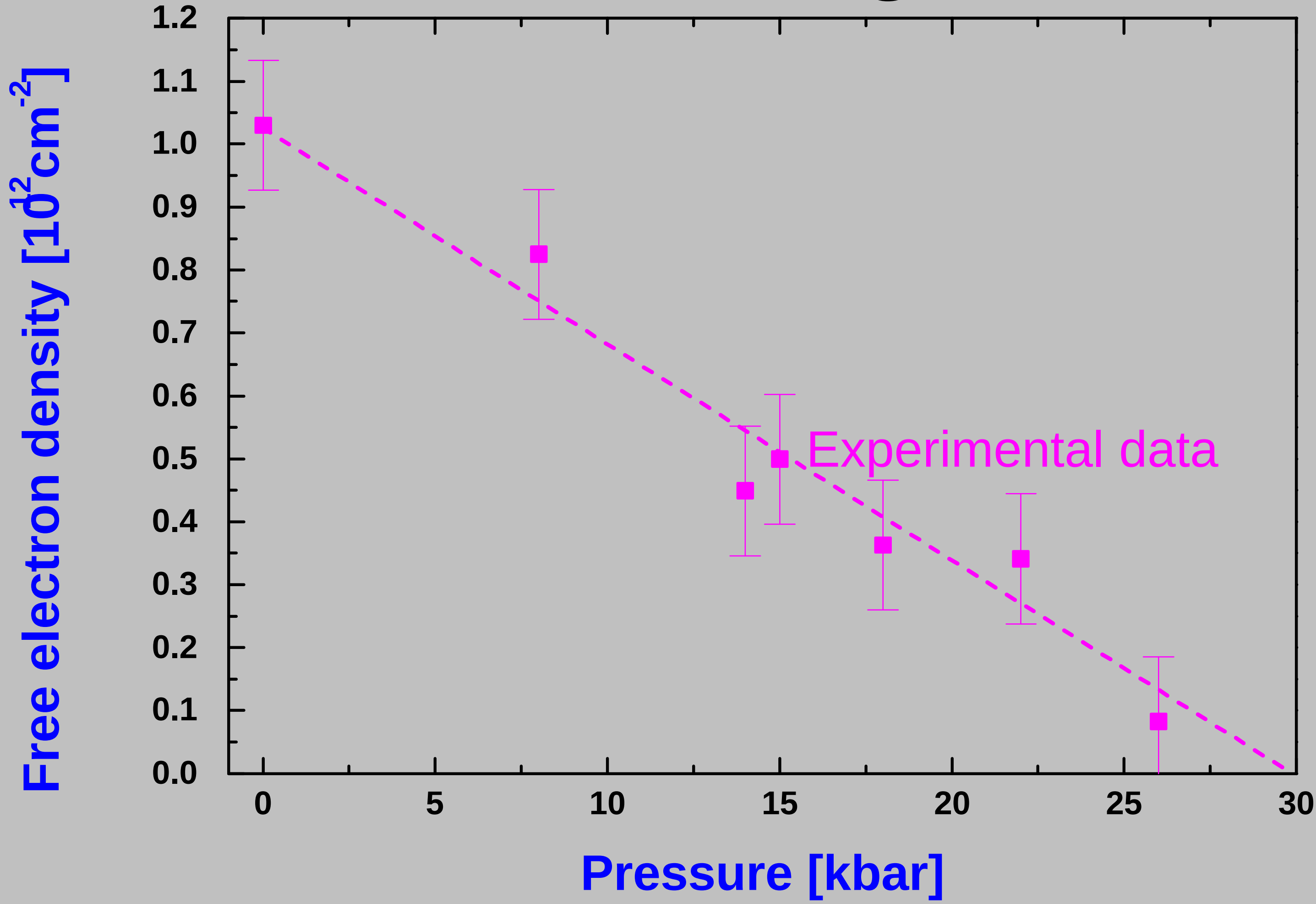
- ☞ **Model Solid Theory.** **C.G. Van de Walle, Phys. Rev. B 39, 1871 (1989)**
- ☞ **Variational Solution of Schroedinger's equation for quantum well states.**
- ☞ **Self-consistent treatment of the electrical potential via Poison's equation.**

**S. K. Singh, Ph.D. Thesis, SUNY at buffalo,(9/98).**




Energy profile calculated at 1atm for the sample studied.

# Calculated Results Including Self Consistency




Experimental data calculated from the area of the CR, as a function of pressure, normalized to the 1atm electron density. The 1atm electron density was determined, from the CR strength and spin splitting. to be $(1.0\pm0.1)\mathrm{x}10^{12}$ cm$^{-2}$.

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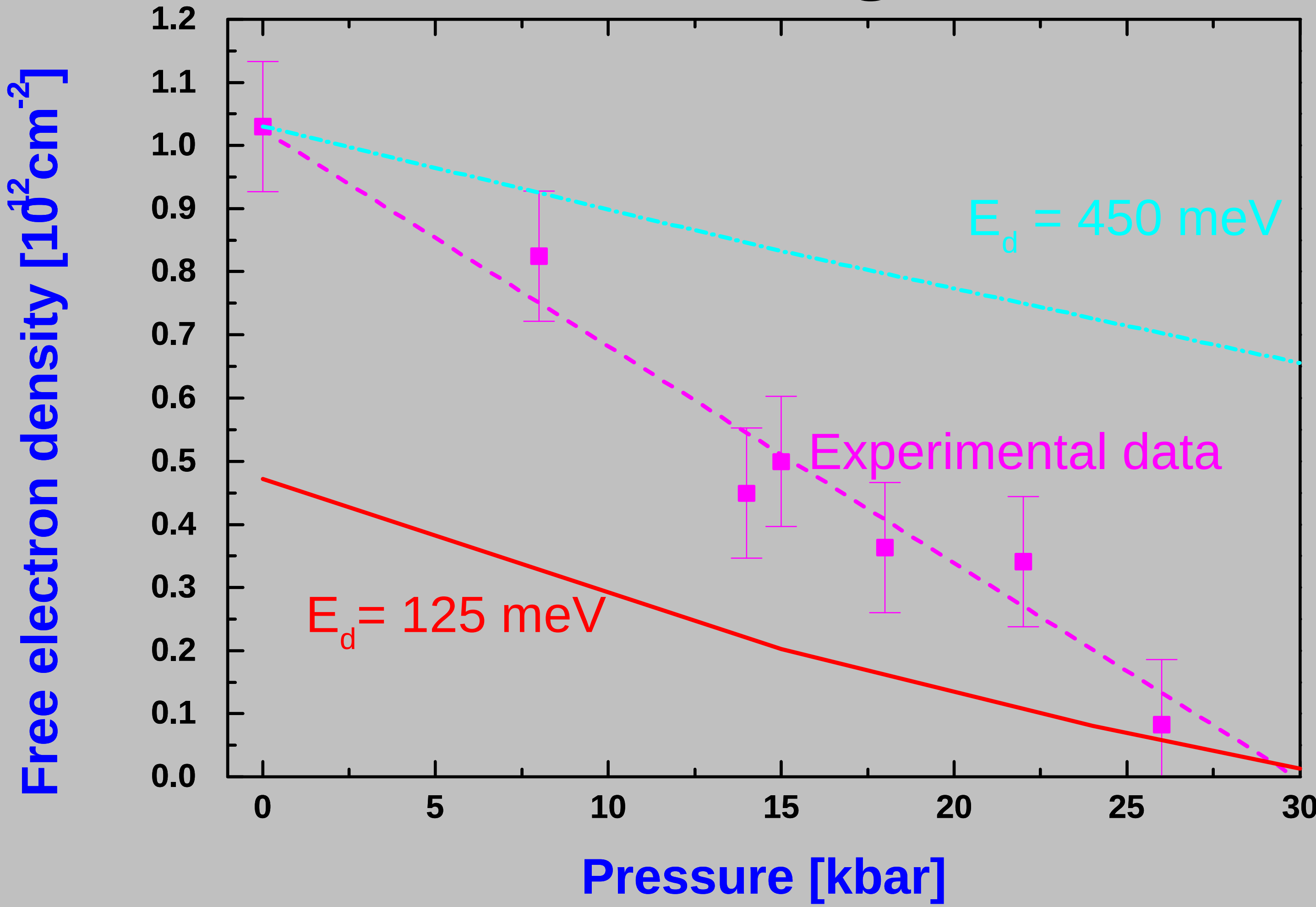


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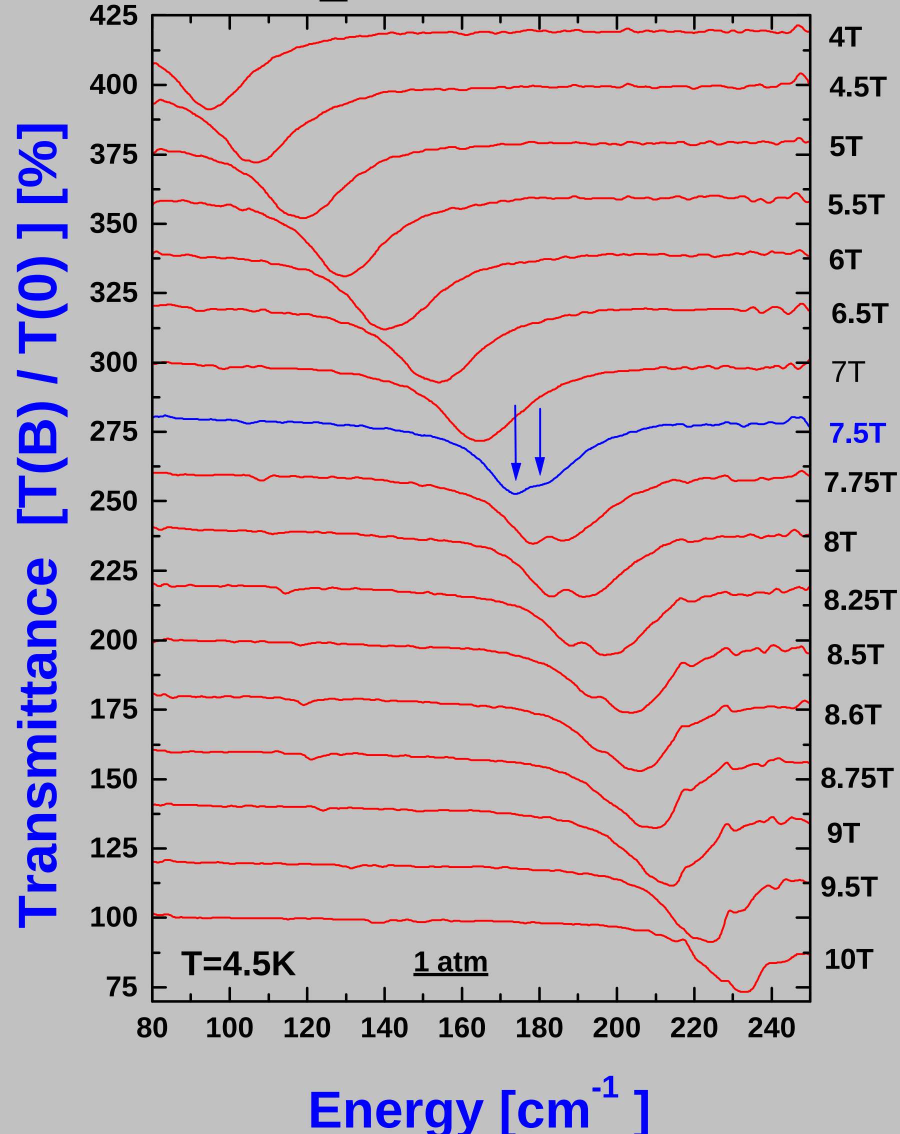
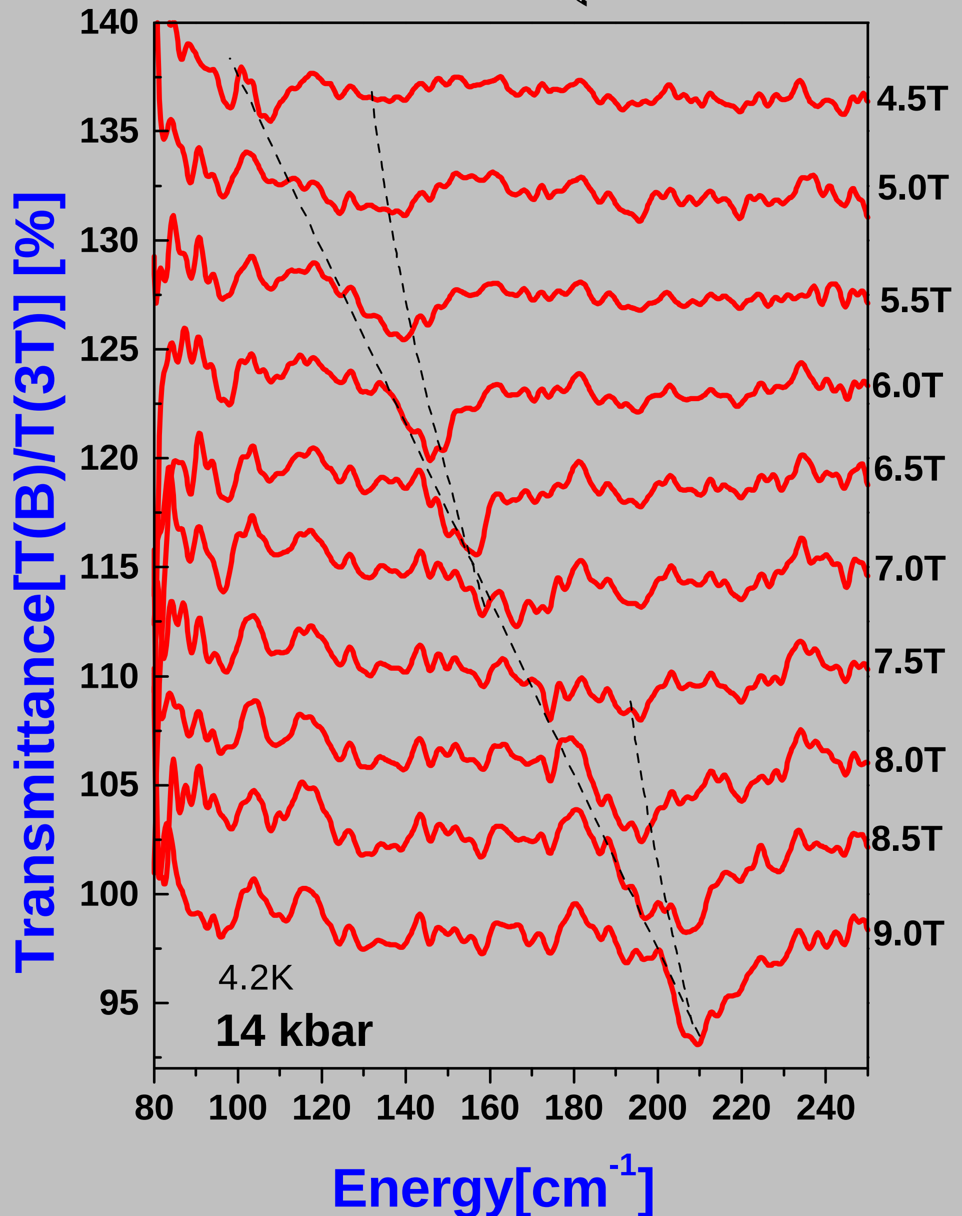
Calculated electron density as a function of pressure assuming a surface donor level at 125 meV and 450 meV respectively from the GaSb valence band.

# Atmospheric Data



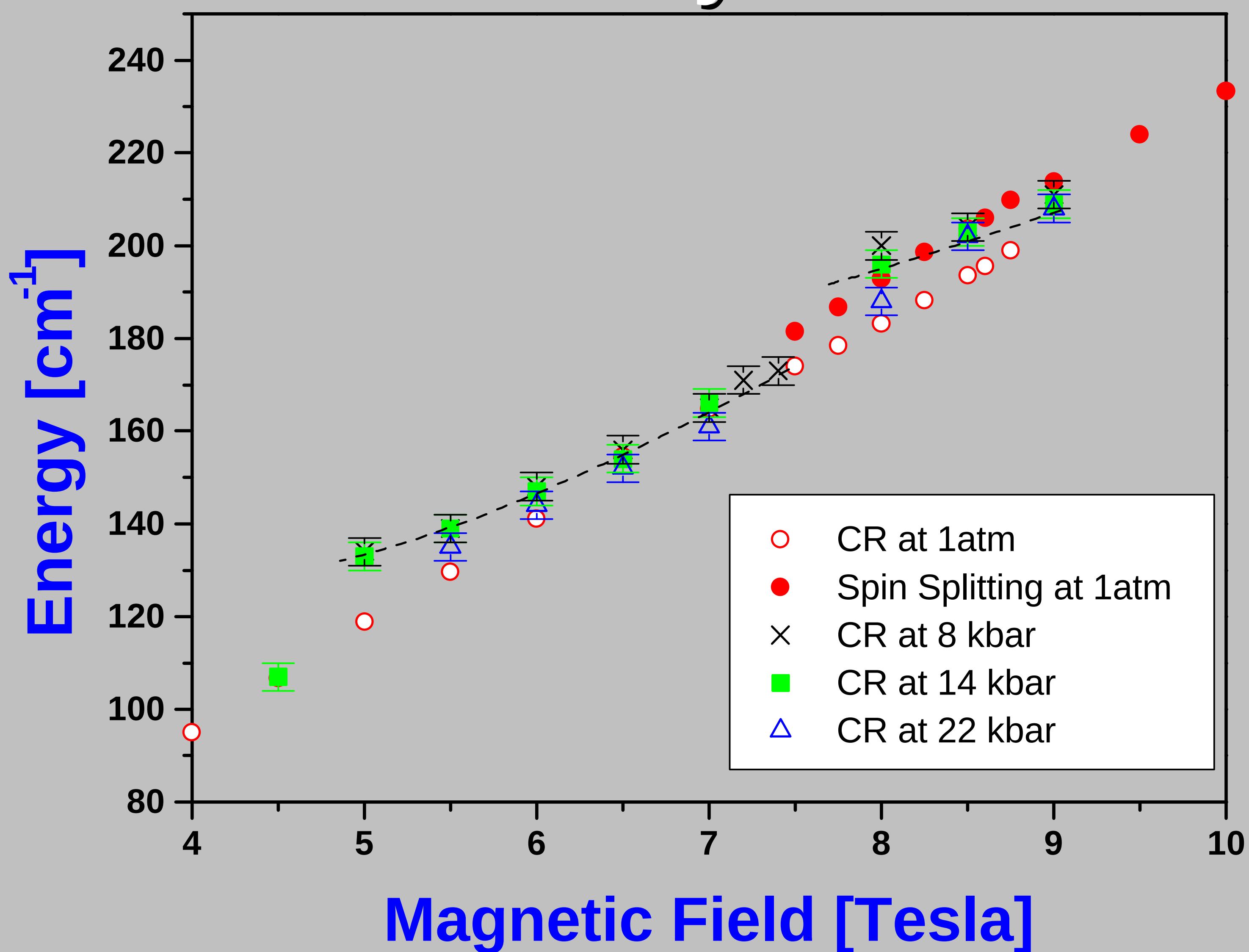

FIR Fourier transform magneto spectroscopy data at 1atm and 4.5K outside the DAC. Notice the spin splitting at ~ 7.5 T shown with the blue trace.

# Pressure Data(14 kbar)




FIR Fourier transform magneto spectroscopy data at 14 kbar and 4.2K

# Summary Plot




Measured magnetic field dependence of the CR at several different pressures.

# Summary and Conclusions

☞ CR was recorded as a function of pressure up to 35 kbar, at 4.2 K, and in magnetic fields up to 9T by FIR Fourier transform magneto-transmission spectroscopy in the spectral region 80 --- 250$cm^{-1}$.

☞ CR quenches at (29±3)kbar.

☞ Assuming the Fermi level is pinned by surface donor states, we employ a model solid calculation in conjunction with a self consistent treatment.

☞ We find that a deep surface state situated 125±25meV above the GaSb valence band can account for the above 29kbar quenching, but can not account for the full electron density at 1 atm.

☞ This implies the existence of an additional source/sink of electrons. This could also explain the interesting behavior of the CR with magnetic field if we consider it to be related to metastable states near the InAs/AlSb interface(Tamm-like States).

☞ We are pursuing more sophisticated calculations and additional experiments in order to explore this possibility.